Interleaved, sampled fiber Bragg gratings for use in hybrid wavelength references

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We discuss the design and fabrication of interleaved, sampled fiber Bragg gratings (ISFBGs) for use in hybrid wavelength calibration references covering the 1300–1600-nm region. We demonstrate use of sampled phase masks (SPMs) to make sampled gratings and ISFBGs. The success of the SPM technique suggests a single-exposure method with an interleaved, sampled phase mask to make ISFBGs.

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1. Introduction

Manufacturers of optical telecommunications components, test equipment, and systems require sufficiently accurate and easy to use wavelength calibration references to ensure the interoperability of their products. In the current dense wavelength division multiplexing bands, this need is met by the National Institute of Standards and Technology's gas-filled absorption cells, e.g., C_2H_2, HCN, and CO, covering the 1510–1630-nm range.[1–3] But this limited wavelength coverage will be insufficient as new technologies (e.g., wideband optical amplifiers, All Wave fiber, and active dispersion management) permit dense wavelength division multiplexing at shorter wavelengths; the foreseeable commercial telecommunications band could extend from below 1300 to above 1600 nm. To provide useful wavelength references throughout this band, without having to find a series of suitable molecules with each covering some small wavelength range, we are developing hybrid wavelength references that use a single fiber Bragg grating (FBG) with multiple reflection peaks over the 1300–1600-nm range.[4] One peak of the multipeaked FBG is locked through temperature feedback to an absorption peak of a gas cell; locking this peak stabilizes the other peaks to their calibrated positions.[4]

The most direct method for making a multipeaked FBG is serial inscription of superimposed FBGs[5]: A

section of photosensitive fiber is exposed to a series of ultraviolet interference patterns, each with a different period, by use of either a two-beam interferometer or a set of phase masks. The result is an overlapping set of oscillations in the refractive-index profile of the fiber core, each of which produces a separate reflection peak. Serial inscription suffers from two inherent problems: It is time-consuming, requiring a separate exposure for each desired peak in the final reflectance spectrum; and the inscription of subsequent peaks degrades those that have been previously inscribed. This degradation has been observed by both Othonos *et al.*[5] and Swann *et al.*[4] An alternative multipeaked FBG is the sampled grating,[6] created when a square-wave amplitude modulation (sampling) is imposed on the refractive-index profile of a regular grating [Fig. 1(a)]. The resulting spectrum consists of a central peak and a series of side peaks. Unfortunately, for a technically feasible sampled FBG, the bandwidth is much smaller than our target 300-nm band.

To overcome the problems of serial inscription and the limitations of sampled gratings, we are now making interleaved, sampled fiber Bragg gratings (ISFBGs)[7–9] using sampled phase masks (SPMs). An ISFBG [Fig. 1(b)] is a set of sampled FBGs in the same length of fiber with nonoverlapping samples or ON regions. The ISFBG design automatically produces ten or more useful peaks in each sampled FBG's band, can cover our target band by interleaving only a few sampled FBGs, and eliminates the degradation problem of serial inscription because the ON sections do not overlap. A SPM [Fig. 2(a)] is a phase mask with transmitting (ON) regions and opaque (OFF) regions. The ON–OFF sampling function of the SPM is transferred to the fiber core during ultraviolet exposure, allowing us to write an
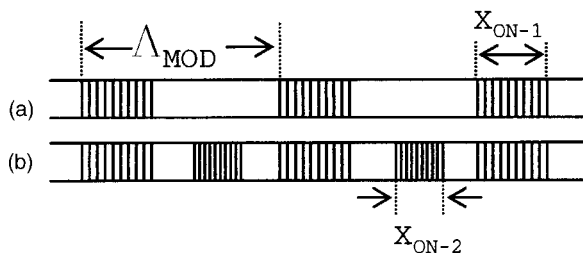
Fig. 1. (a) Schematic diagram of a sampled FBG written in an optical fiber. Vertical lines indicate maxima in the refractive-index profile. (b) Schematic diagram of an ISFBG. The amplitude modulation periods of the interleaved gratings are the same (Λ_{MOD}), but the sample lengths (X_{ON-1} and X_{ON-2}) can be different.

entire sampled FBG with one exposure. Our FBG fabrication method is similar to the two-mask method recently employed by Durand *et al.*,[10] but combines the amplitude and phase masks into one combined mask. The SPM method retains the ease of use and repeatability of traditional phase masks, and only a few exposures (each with a different SPM) are needed to make our desired ISFBG. Furthermore, it is possible to combine the interleaving and sampling actions into one mask [Fig. 2(b)], an interleaved, sampled phase mask (ISPM), hence allowing us to make an ISFBG with a single ultraviolet exposure.

In this paper we show that ISFBGs can be used to produce wavelength calibration references throughout the 1300–1600-nm region, demonstrate for the first time to our knowledge the SPM technique for making ISFBGs, and discuss the design of an ISPM
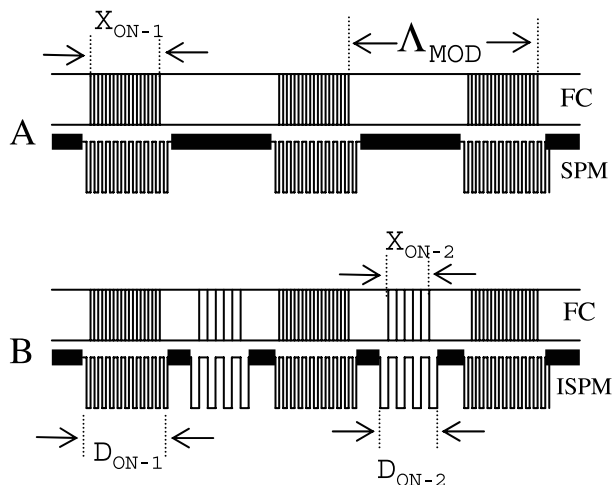

Fig. 2. (a) Schematic diagram of the SPM technique. Ultraviolet light passes through the SPM from the bottom of the page and then onto the fiber core (FC). The phase mask grooves are indicated in the SPM; thick lines on the front face of the SPM indicate opaque (metal) regions. Vertical lines across the fiber core indicate maxima in the refractive-index profile, as in Fig. 1. (b) Schematic diagram of an ISPM with two interleaved patterns. Neighboring ON regions with different values of Λ_{PM} must be sufficiently separated to prevent interference between their +1 and −1 diffraction orders.
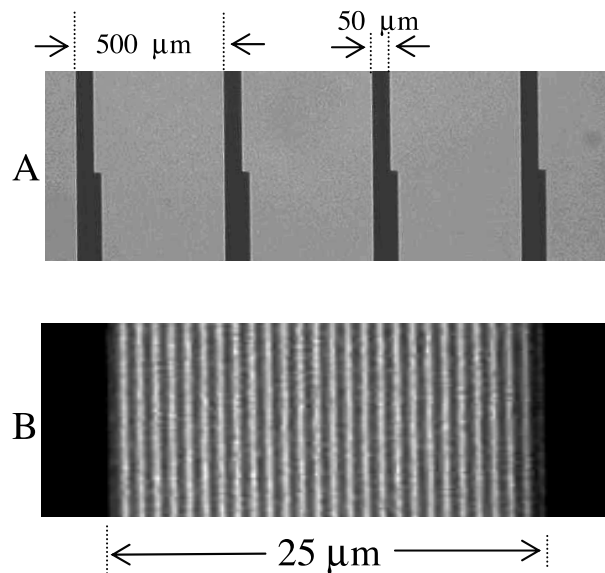

Fig. 3. (a) Reflected light photomicrograph of SPM-1. Brighter regions are the opaque metal overcoat (Al); darker regions contain phase mask grooves. D = 50 and 75-μm regions are shown. During exposure, the fiber lies horizontally across the mask. (b) Phase mask grooves visible in transmitted light photomicrograph over the D = 25-μm section of SPM-1.

for single-exposure fabrication of ISFBGs covering our target band.

2. Methods

We make SPMs using contact photolithography on commercially available phase masks, depositing an opaque metal film (10-nm Ti and 140-nm Al) onto the OFF regions of the SPM. The metal film lies directly on the phase mask grooves (~250 nm deep) on the front face of the SPM. The ON regions are cleared during a lift-off step, leaving clean boundaries between the ON and OFF regions of the SPM. Figure 3 shows SPM-1, which has a phase mask groove period Λ_{PM-1} = 1.06435 μm and an amplitude modulation (sampling) period Λ_{MOD} = 500 μm. This SPM produces sampled FBGs with reflectance peaks centered around $\lambda_c \sim$ 1540 nm. The lengths of the ON sections patterned on this mask are D_{ON} = 25, 50, 75, and 100 μm [the 50- and 75-μm sections are shown in Fig. 3(a)]. Patterning different values of D_{ON} and Λ_{MOD} on the same SPM allows us to alter the properties of the resulting gratings by simply translating the SPM without having to change masks. Typical alignment and edge quality are shown in Fig. 3(b), along with a view of the phase mask grooves for the D_{ON} = 25-μm section.

To make sampled FBGs, we expose a section of H$_2$-loaded photosensitive fiber to a cw 244-nm laser beam through the SPM using telescopes and a final cylindrical lens to concentrate the beam onto an L = 17-mm length of fiber. Typical exposure times are 2–15 min with an intensity of approximately 2.5 W/cm^2. The fiber and SPM positions are controlled by standard mechanical stages to ensure that the
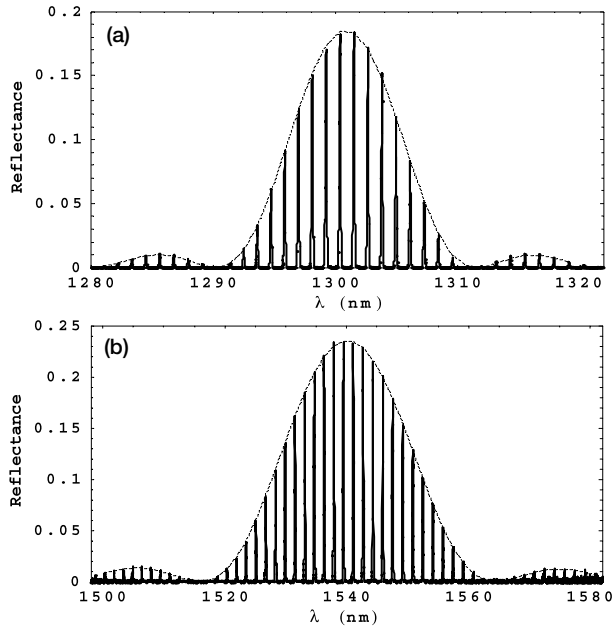
Fig. 4. Reflectance spectrum of an ISFBG. Resolution bandwidth is 100 pm. (a) Spectral region that is due to SPM-2; dotted curve is the envelope function given in expression (1) by use of least-squares fitting parameters of $n_1 = 1.03 \times 10^{-4}$, $\Delta\lambda_{\mathrm{BW}} = 21.4$ nm, and $\lambda_C{}^* = 1300.89$ nm. (b) Spectral region that is due to SPM-1; dotted curve is same as in (a), with $n_1 = 2.25 \times 10^{-4}$, $\Delta\lambda_{\mathrm{BW}} = 48.7$ nm, and $\lambda_C{}^* = 1540.02$ nm.

Fig. 5. Closeup of the central regions' reflectance spectra of ISFBG. Otherwise same as Fig. 4.

fiber is properly aligned and held in contact with the front face of the SPM over the exposed length, hence minimizing unwanted diffraction effects. To interleave sampled FBGs, we perform multiple exposures using different SPMs, e.g., SPM-1 ($\lambda_{c\text{-}1} \sim 1540$) and SPM-2 ($\lambda_{c\text{-}2} \sim 1300$). SPM-2 has the same parameters as SPM-1 but with $\Lambda_{\mathrm{PM}\text{-}2} = 0.897$ μm. Interleaving is ensured when we monitor the relative positions of the opaque (OFF) regions of each SPM with a microscope and video monitor to ensure that the ON regions of the second SPM lie in the OFF regions of the first. Reflectance spectra $R(\lambda)$ are measured with fiber-coupled LEDs as light sources and an optical spectrum analyzer.

3. Results

Figure 4 shows the reflectance spectrum of an ISFBG made with SPM-2 ($D_{\mathrm{ON}} = 75$ μm) and then SPM-1 ($D_{\mathrm{ON}} = 50$ μm), each with a 3-min exposure. As expected, there are two bands of peaks, one around 1540 nm with bandwidth $\Delta\lambda_{\mathrm{BW}\text{-}1} \sim 50$ nm and one around 1300 nm with bandwidth $\Delta\lambda_{\mathrm{BW}\text{-}2} \sim 20$ nm. The envelope shape for each band is due to the square-wave amplitude modulation of the grating, and sidelobes are visible in both bands. The tallest peak in each band is located at $\lambda_{c\text{-}1} = 1539.45$ nm ($R = 0.23$) and $\lambda_{c\text{-}2} = 1301.52$ nm ($R = 0.18$). The spacing between peaks is $\Delta\lambda_{\mathrm{SEP}\text{-}1} = 1.63$ nm near 1540 nm and $\Delta\lambda_{\mathrm{SEP}\text{-}2} = 1.16$ nm near 1300 nm; these values are within 10 pm of the values expected from the modulation period $\Lambda_{\mathrm{MOD}} = 500$ μm. Fifteen
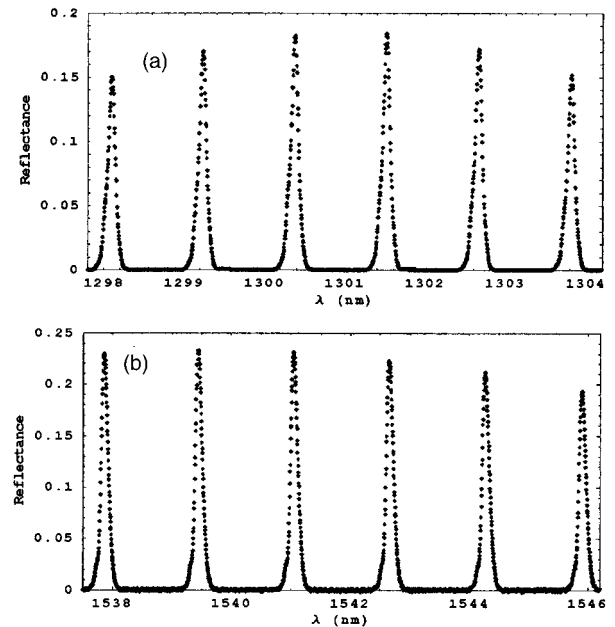
peaks in the 1540-nm band have reflectances $R > 0.1$ and widths $\delta\lambda_{\mathrm{FWHM}} \sim 100$ pm; eight peaks in the 1300-nm band also have $R > 0.1$ and widths $\delta\lambda_{\mathrm{FWHM}} \sim 60$ pm (with spectrum analyzer resolution of 20 pm). One of our noninterleaved, sampled FBGs has a reflectance spectrum (not shown) containing nine peaks with $R > 0.5$ and 26 peaks with $R > 0.1$ over a 40-nm region, demonstrating that the SPM technique can make strong reflectance peaks over a wide band. As shown in the detailed view of the spectrum of the interleaved grating near the center of each band (Fig. 5), the peaks made by the SPMs are similar in shape and are free of spurious features.

The simplest model of our sampled gratings assumes a sinusoidal refractive-index oscillation with a binary amplitude modulation. The period of the amplitude modulation is Λ_{MOD}, and the length of each ON section is X_{ON}. Within an ON section, the index oscillation is $\Delta n \cos(2\pi x/\Lambda_{\mathrm{F}})$, where $\Lambda_{\mathrm{F}} = \Lambda_{\mathrm{PM}}/2$ and x is the coordinate along the fiber. The overall grating length is L, and $L \gg \Lambda_{\mathrm{MOD}} > X_{\mathrm{ON}} \gg \Lambda_{\mathrm{PM}}$. Using this model, we expect the spacing between reflectance peaks to be $\Delta\lambda_{\mathrm{SEP}} \approx 2n_{\mathrm{EFF}} \Lambda_{\mathrm{F}}{}^2/\Lambda_{\mathrm{MOD}}$ (where n_{EFF} is the average effective index of the fiber), in agreement with the measured values mentioned above. From the peak reflectance and the envelope widths, we estimate Δn, finding $\Delta n \sim 1 \times 10^{-4}$ for the first exposure (SPM-2, 1300-nm band) and finding $\Delta n \sim 2 \times 10^{-4}$ for the second exposure (SPM-1, 1540-nm band). The predicted shape of the envelope of reflectance peaks is

$$\tanh^2\left\{\frac{\Delta n \pi X_{\mathrm{ON}} L}{\lambda \Lambda_{\mathrm{MOD}}} \operatorname{sinc}\left[2\frac{(\lambda - \lambda_C{}^*)}{\Delta\lambda_{\mathrm{BW}}}\right]\right\}, \qquad (1)$$

where λ_c^* is the center of the envelope. Fitting the maxima of the reflectance peaks to expression (1) allows us to extract λ_c^*, $\Delta\lambda_{BW}$, and Δn (see Fig. 4). We expect $\lambda_c^* = \lambda_c = n_{EFF}\Lambda_{PM}$, i.e., the envelope center coincides with the tallest peak, and its location is dictated by the phase mask groove period. Instead we find $\lambda_{c\text{-}1}^* - \lambda_{c\text{-}1} = 0.57$ nm and $\lambda_{c\text{-}2}^* - \lambda_{c\text{-}2} = -0.63$ nm; constraining $\lambda_C^* = \lambda_C$ produces an unsatisfactory fit (not shown) that does not significantly alter $\Delta\lambda_{BW}$ or Δn. The asymmetry of the envelope with respect to the tallest peak shows that the index profile is more complicated than that used in the simplistic model to derive expression (1), indicating the need for a more complete model. In addition, the stronger sampled FBG discussed above (maximum $R > 0.5$) deviates significantly from expression (1), suggesting that the nonlinearity of the index change is relevant at $\Delta n \sim 10^{-3}$, e.g., the index change could be saturating.

For sampled gratings made with a SPM, Λ_{PM} determines λ_C, and Λ_{MOD} dictates $\Delta\lambda_{SEP}$. Similarly, we might expect D_{ON} to determine $\Delta\lambda_{BW}$, but $\Delta\lambda_{BW}$ and the envelope shape are also affected by diffraction as the ultraviolet light propagates from the SPM surface ($z = 0$) to the photosensitive fiber core ($z = z_F$). For the (physically unattainable) limit of $z_F = 0$, $\Delta\lambda_{BW}^{(0)} \approx n_{EFF}\,\Lambda_{PM}^2/D_{ON}$. Calculations with the Rayleigh–Sommerfeld equation and the observations of Durand et al.[10] indicate that, in the region close to the mask, $\Delta\lambda_{BW}$ increases with z_F. This result is consistent with our finding that $\Delta\lambda_{BW} \approx 1.4\Delta\lambda_{BW}^{(0)}$, but quantitative agreement will require a more sophisticated model, e.g., one that includes diffraction, the nonlinearity of the ultraviolet-induced index change, and the finite extent of the photosensitive region of the fiber.

4. Discussion and Conclusion

As shown in Fig. 2(b), the ISPM combines the interleaving and sampling operations into one mask. The beauty of this design is that it has the potential to make an ISFBG with one ultraviolet exposure. The SPM can be thought of as a preliminary step toward the ISPM. That our SPMs work well is strong evidence that the ISPM will work also. As a design example, consider the interleaving of four SPMs with the following parameters: $\Lambda_{MOD} = 500$ μm; $D_{ON} = 50$ μm; and $\Lambda_{PM} = 0.914$, 0.969, 1.024, and 1.076 μm. There would be 75-μm metalized regions between each ON section of this ISPM. For $n_{EFF} = 1.45$, we expect $\lambda_C = 1325$, 1405, 1485, and 1560 nm; $\Delta\lambda_{SEP} = 1.21$, 1.36, 1.52, 1.68 nm; and $\Delta\lambda_{BW} \sim 36$, 41, 46, and 51 nm, respectively. Given our results with SPM-1 and SPM-2, we would expect >70 useful peaks covering >260 nm of our 300-nm target band. To avoid the interference of $+1$ and -1 orders of neighboring ON sections from interfering, we would expose fibers in contact with the mask. The regions of common Λ_{PM} must be phase coherent, and the zeroth-order diffraction intensity must be nulled to the same extent as in regular phase masks. Although the fabrication of the ISPM is more complicated than a SPM, both electron-beam lithography and holographic contact lithography should work to pattern the phase mask grooves. Metalization would be done by use of the same contact lithography and deposition methods used for SPMs, although with alignment marks to ensure proper interleaving. It should be noted that constant spacing between reflectance peaks is not incorporated in the design parameters described above and is not required for a hybrid wavelength reference. For applications requiring constant spacing, Λ_{MOD} becomes a function of Λ_{PM}, which would significantly complicate the fabrication of the ISPM.

ISFBGs are a promising design for artifacts in a hybrid wavelength reference. We have reported here on the first ISFBGs made by the SPM technique. Our success making sampled gratings with SPMs strongly encourages our pursuit of the ISPM. The ISPM is potentially a single-exposure fabrication method for ISFBGs.

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